Learning SysML Modeling for Space Applications
(as inspired by the Apollo Program)

A) Team A5 Command & Service Module: Electrical Power Subsystem
B) NASA FireSat II Research

AE 4699 MAV Undergraduate Research
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By: Andrew Silverstein

Academic Course Advisor:
Prof. Dimitri Mavris

Research Advisors:
Dr. Selcuk Cimtalay & Dr. Russell Peak
Sultan Hashmi

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Advisor's Signature: ___________________________

School of Aerospace Engineering
Georgia Institute of Technology

Section A: Team A5 Command & Service Module

I. Team A5 - Model Purpose & Overview

The team for this project consisted of the following undergraduate students: Dong Gweon, Nick Kiratzis, Jake Anderson, and Andrew Silverstein.

As the complexity of systems continuously compound over time, there is an ever increasing need for widespread collaborative development amongst many of the world's most advanced industries. In response to this need, model-based systems engineering (MBSE) is establishing itself as a powerful methodology for integrating different steps of the systems development lifecycle. In conjunction with MBSE, general purpose modeling languages such as SysML are proving to be powerful tools, enabling greater cohesion by standardizing model architectures. The primary objective of this project was to gain experience with the MBSE workflow, from defining physical structures, to interfacing with others' systems, to conducting live parametric analyses.

In particular, the task laid out for this project was to create a parametric SysML model based on a vehicle from the Apollo program, complete with interdependent subsystems and executable instances. Our team chose to focus on modeling the command and service module (CSM) during cislunar flight. The four subsystems we each took individual responsibility over were: radio communications, electrical power, orbital mechanics, and rocket propulsion. The radio communications subsystem determines the power required to downlink a range of signals to the ground station on earth, as well as calculating the signal strength that the ground station will detect at its receiver. The electrical power subsystem calculates the amount of energy available in the CSM, as well as the amount of water that is produced as a byproduct of the fuel cell energy generation. The orbital mechanics package represents the flight computer which computes the orbital trajectory in transit from Earth to the Moon, including corrections and commands to control the attitude and propulsion of the CSM. Finally, the rocket propulsion subsystem performs all necessary calculations to predict burn time for various orbital maneuvers and adjustments.

The organization of the Group A5 system model is conveyed through the package diagram in Figure 1. Our system model involved a decomposition of the *CSM System* top-level block. All elements of the CSM are contained in the *CSM Structure* package, which is organized according to each top-level subsystem block and its corresponding package containing all subsystem elements and diagrams. Additionally, a component of the communication and orbital mechanics subsystems is interfacing with external systems. In the case of the radio communications subsystem, external elements were modeled by the creation of the external blocks *Environment* and *USBGroundStation*, which can be seen in Figure 1 in the system package diagram. In the case of the orbital mechanics subsystem, the external elements *Moon* and *Earth* were modeled with blocks internally.

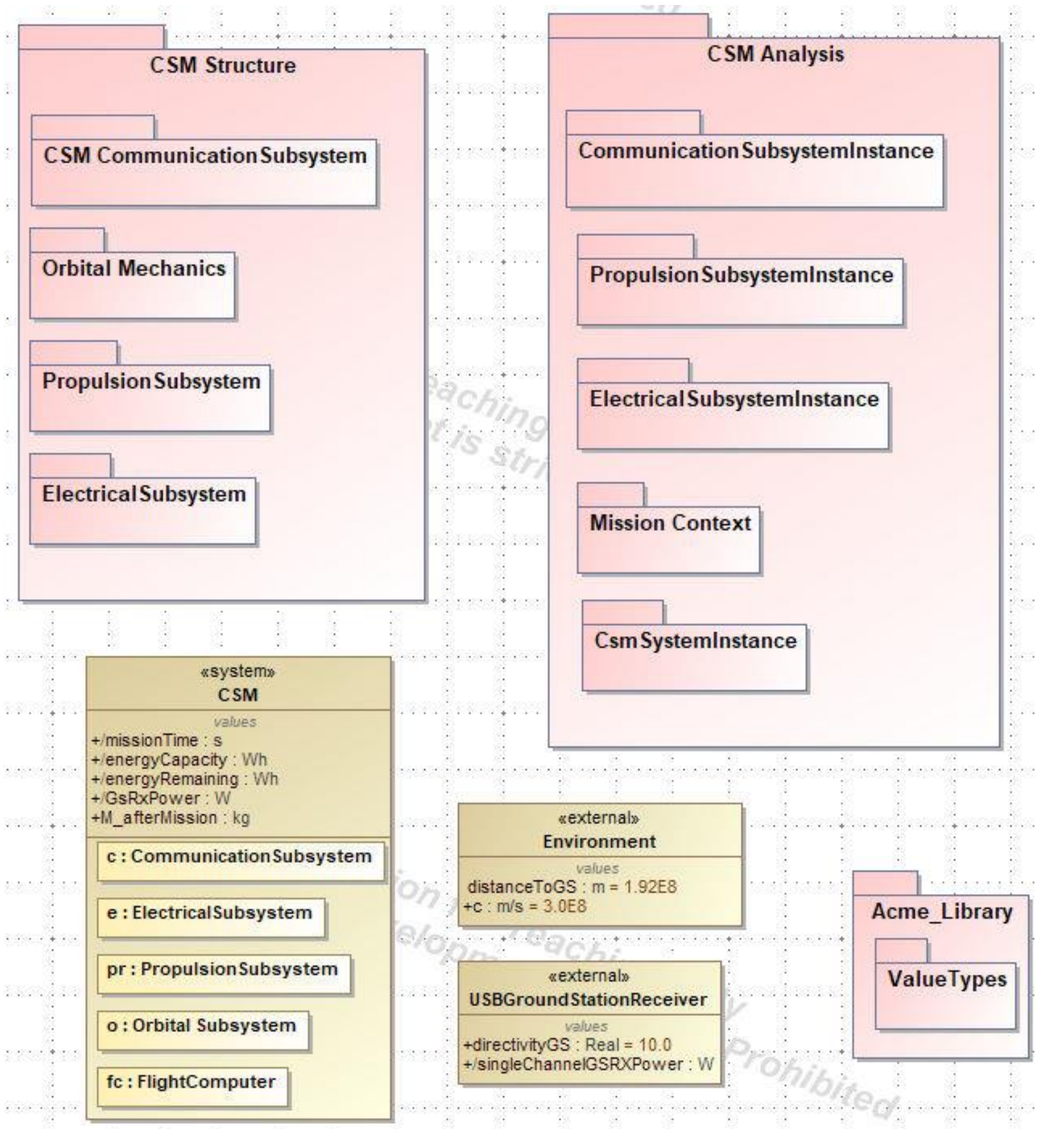

Figure 1 – Main package diagram displaying team's overall model layout and top-level blocks.

All subsystem instances were created in the CSM Analysis package, where parametric analysis was performed using the ParaMagic plugin with OpenModelica as a back-end solver. For the project, a requirement to use explicit value types during the creation of value properties for all calculations. Therefore, the value types defined in the provided *Acme_Library* were used for the creation of all the value properties. Although a constraint block library was also provided, custom constraint blocks were made for all calculations. The block definition diagram featured in Figure 2 displays the decomposition of our model. Each subsystem produces a value property for its own mass, which are all combined to compute the total system mass. Additionally, each subsystem produces unique values as well as values that contribute to system wide performance. Once our full system instance was generated, ParaMagic was used to calculate the top-level parameters and performance metrics, which were then populated directly back into our SysML model. Many of these values can be seen listed under the CSM block values in Figure 2, such as mission time elapsed, energy capacity available, and power transferred to ground station.

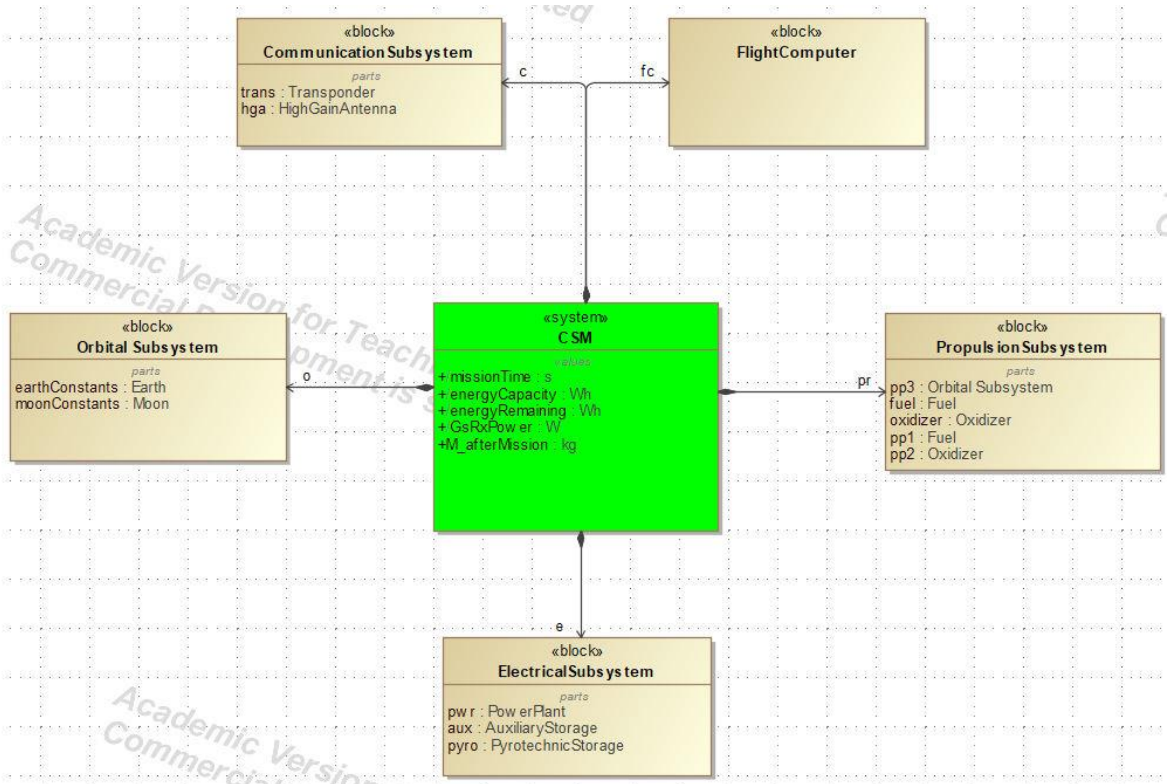

Figure 2 – Block definition diagram of the system with connected subsystems.

II. Overview of My Work – Andrew Silverstein

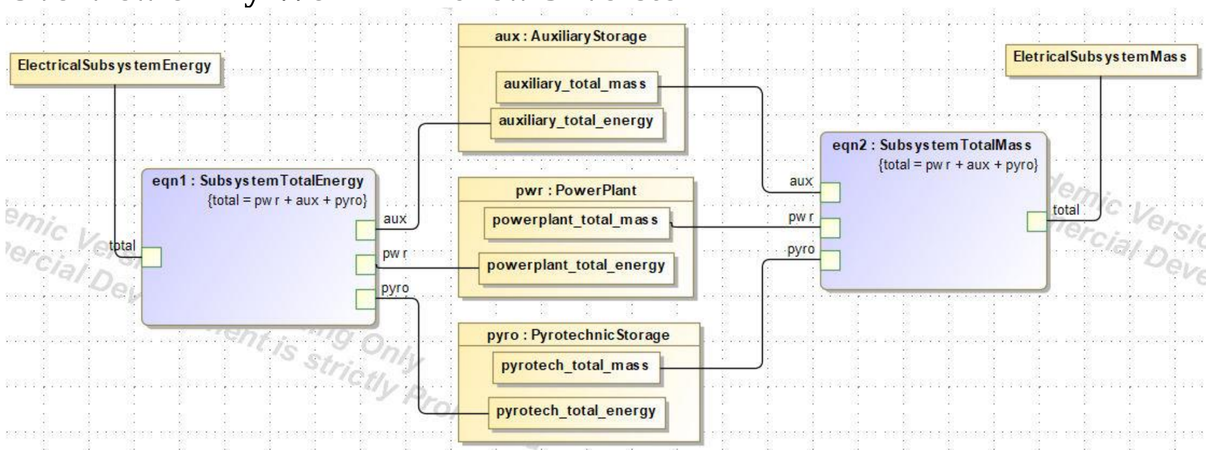

Figure 3 – Parametric diagram of my electrical power subsystem block.

I personally was in charge of modeling the electrical power subsystem of the command and service module. The primary function of the power subsystem is to generate and store electrical energy, which can then be utilized for other systems such as communications, life-support, and guidance. A secondary, but crucial, aspect of the electrical subsystem is drinking water for the crew conveniently produced from the fuel cell reactions. Although the electrical power subsystem also consists of the electrical distribution for the CSM, I chose to focus on the power supply components for my model. Namely, I broke my subsystem up into an auxiliary storage unit, a fuel cell power plant, and a pyrotechnics battery bank.

As the main power storage component for the command and service module, the auxiliary storage system has the important role of acting as a buffer between the power plant and the rest of the CSM. The auxiliary batteries could also be used as an emergency power reserve if any of the power plants should fail, exactly of which happened during the Apollo 13 mission. The model assumes the bank is composed of one battery type wired in parallel, as in the actual CSM. The mass and energy capacity of the auxiliary bank is therefore determined by an individual battery's nominal voltage, capacity, and mass, along with a value property describing the quantity of batteries. The SysML parametric diagram for the auxiliary storage is shown below.

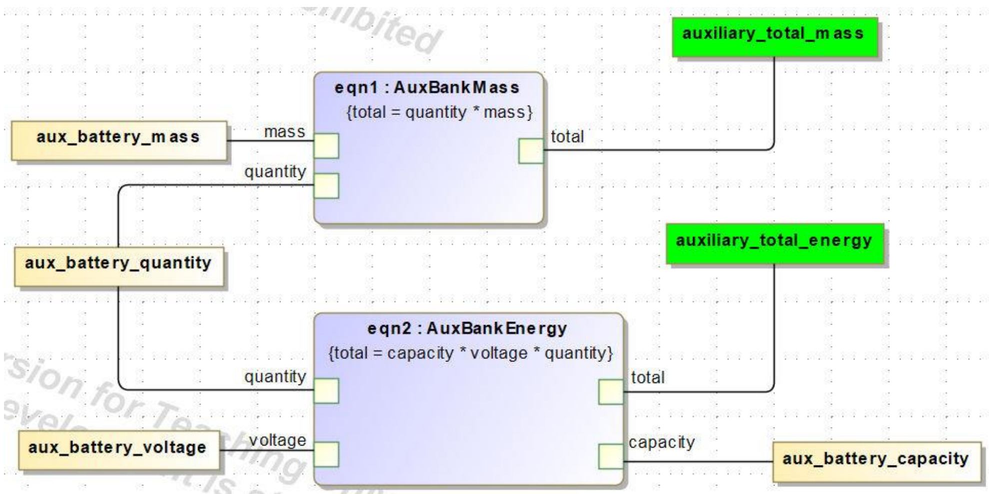

Figure 4 – Parametric diagram of the auxiliary storage subsystem.

Parametric diagrams were also created for the power plant and pyrotechnic storage aspects of the electrical power subsystem. The power plant is the most complex out of the three systems that compose the electrical subsystem. The parametric diagram outlining the power plant is shown in Figure 5. The capacity of liquid hydrogen (LH_2) and liquid oxygen (LOX) tanks are given and summed to find the total respective mass for each reactant. These total masses for each reactant are inputted into the power plant total mass equation. At the same time, the amount of hydrogen is used to compute the amount of water available to be produced by multiplying stoichiometric factors. This technique assumes hydrogen is the limiting reagent, which limits the flexibility of this diagram. In the future, it is possible to incorporate a logic function to dynamically determine the limiting reagent in order to more accurately calculate water produced. This mass value of the water available is wired into an equation where it is multiplied by the fuel cell operating voltage and a conversion efficiency factor to give the total available energy for a single fuel cell. The conversion efficiency is a constant value that for the CSM instance was calculated backwards from Apollo datasheets specifying water production for various power draws on a fuel cell. The singular fuel cell energy is finally multiplied by the quantity of fuel cells in the spacecraft's stack in order to find the total energy available to be generated. This same fuel cell quantity value is multiplied by the mass of a single fuel cell to find the total fuel cell stack mass, which is summed with the reactants to equal the power plant's total mass.

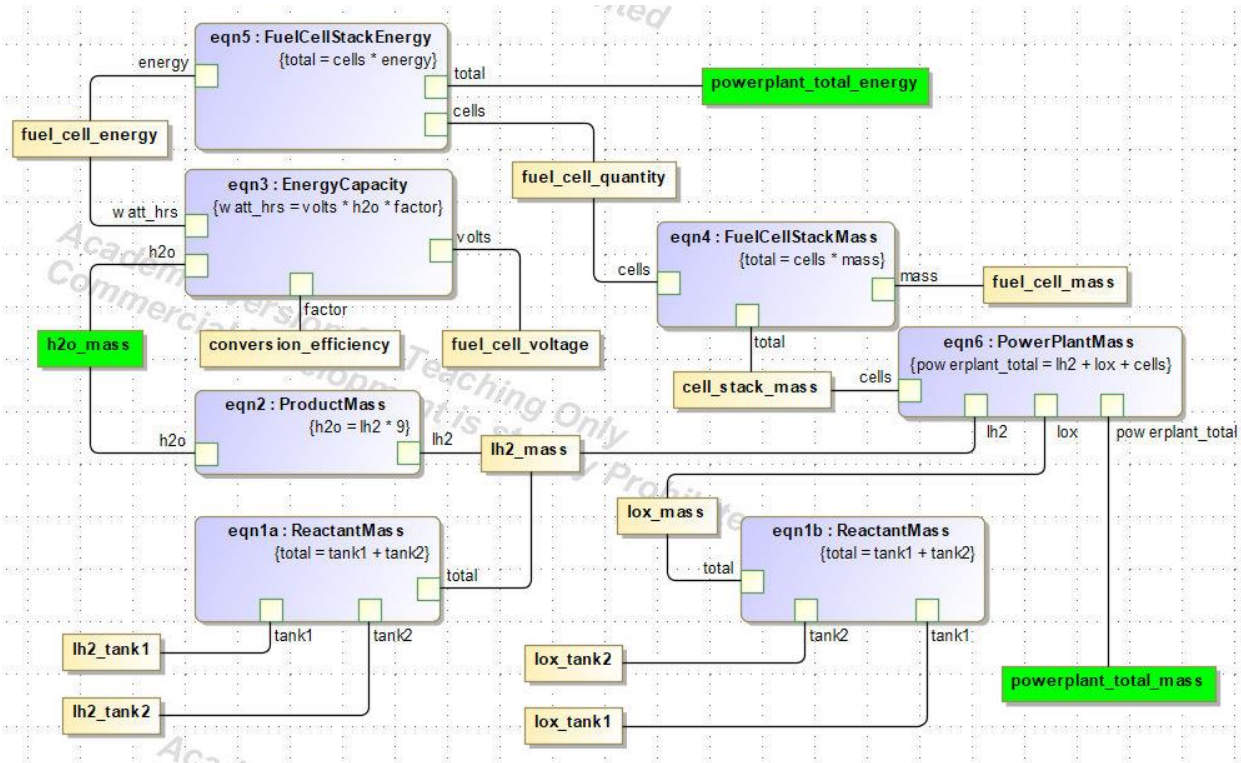

Figure 5 – Parametric diagram of the power plant subsystem.

Figure 6 outlines the inputs and outputs of the pyrotechnic storage system. The pyrotechnic batteries hold a much smaller charge than the auxiliary batteries, as they are only used to detonate charges during stage separations. The pyro batteries also have different voltage and mass characteristics, and unlike the auxiliary storage batteries, the pyrotechnic battery bank cannot be recharged by the power plant. Despite these differences, as well as having a different quantity of batteries in the default CSM instance, this system has a very similar parametric subsystem to the auxiliary storage subsystem due to both having similar behaviors.

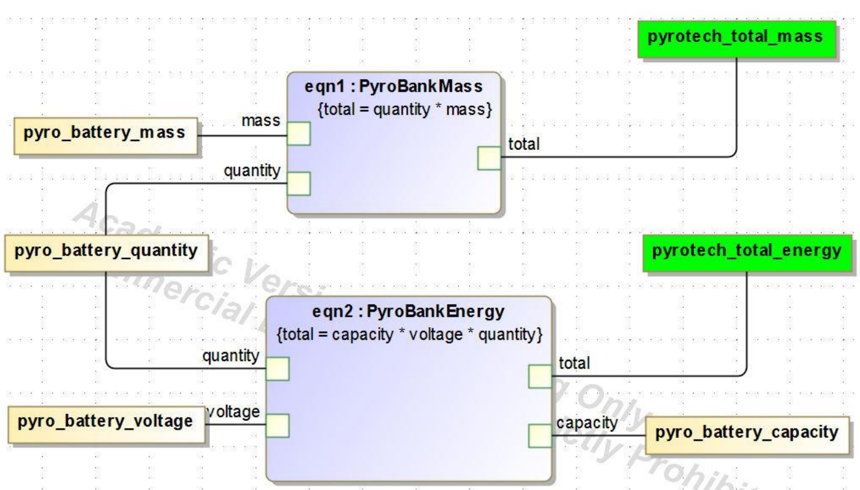

Figure 6 – Parametric diagram of the pyrotechnic storage subsystem.

An instance named *eecoms1* (named after flight control position in charge of electrical, environmental, and consumables management) was created for the electrical power subsystem to demonstrate the flexible capabilities of the parametric model. The ParaMagic tool was used to prescribe the given and target values for the instance and compute the results by implementing OpenModelica as the math solver. For this instance, all of the values that were considered given were assigned their default values as determined from NASA's own archival data on the command and service module systems. All remaining values were listed as targets, and were successfully solved for. The next figures below show ParaMagic solving the model and an instance block definition diagram populated with the values for the total subsystem. Following the instance figures, two "DNA signatures" from the Panorama tool are provided to aid in visualizing the interconnectivity within my subsystem and depicting the cohesion of the team's model as a whole.

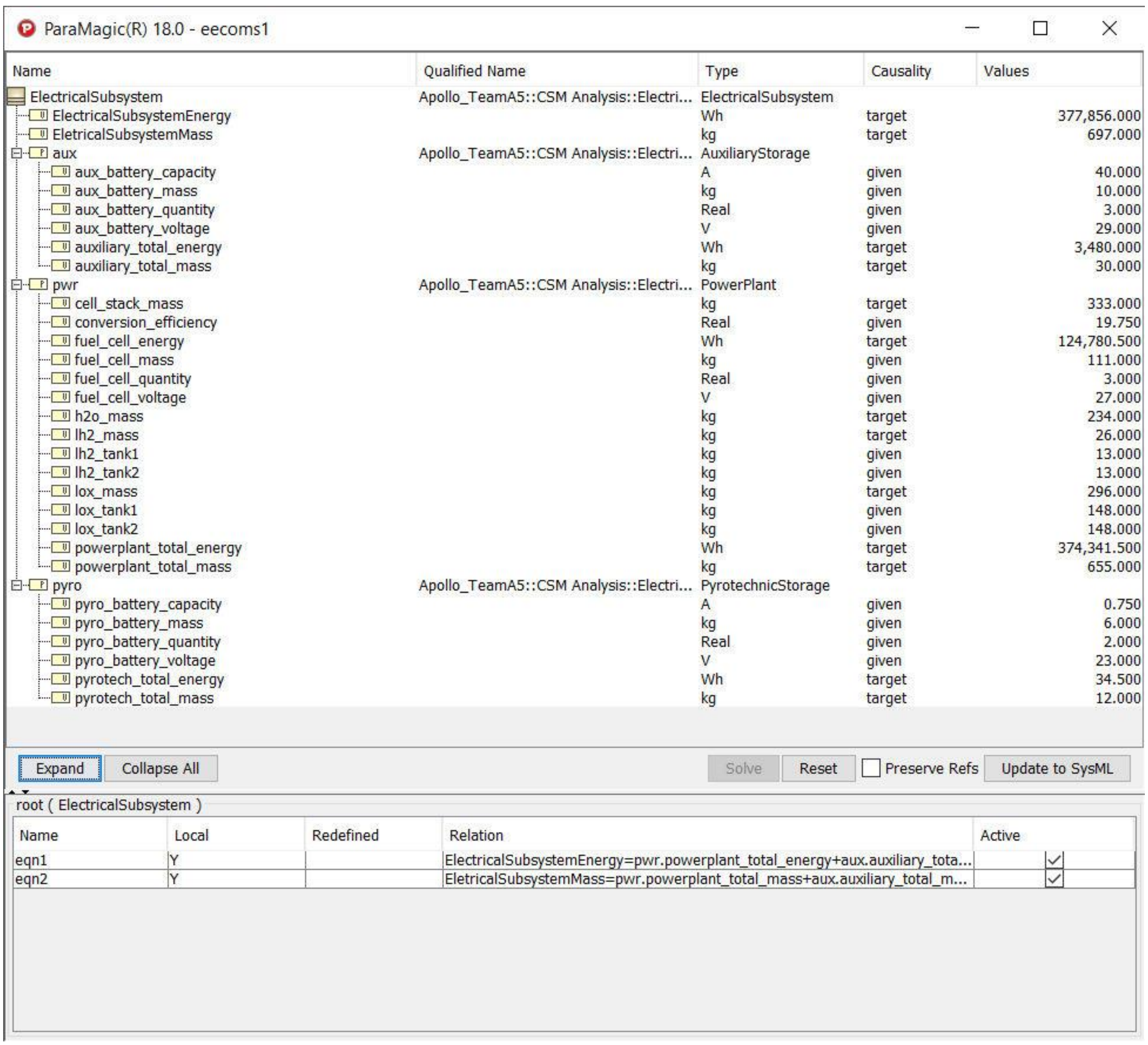

Figure 7 – ParaMagic calculating values for the electrical power subsystem for the *eecoms1* instance based on values from the actual Apollo Command and Service Module.

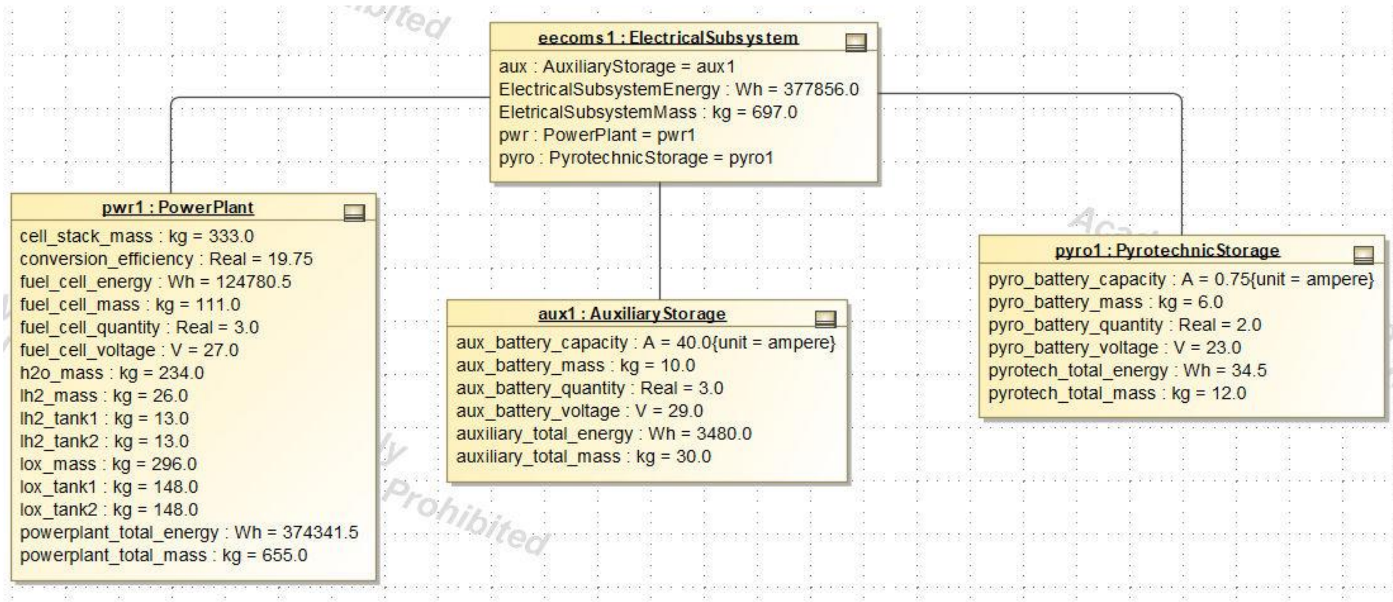

Figure 8 – *Eecoms1* instance block definition diagram of electrical system with updated values.

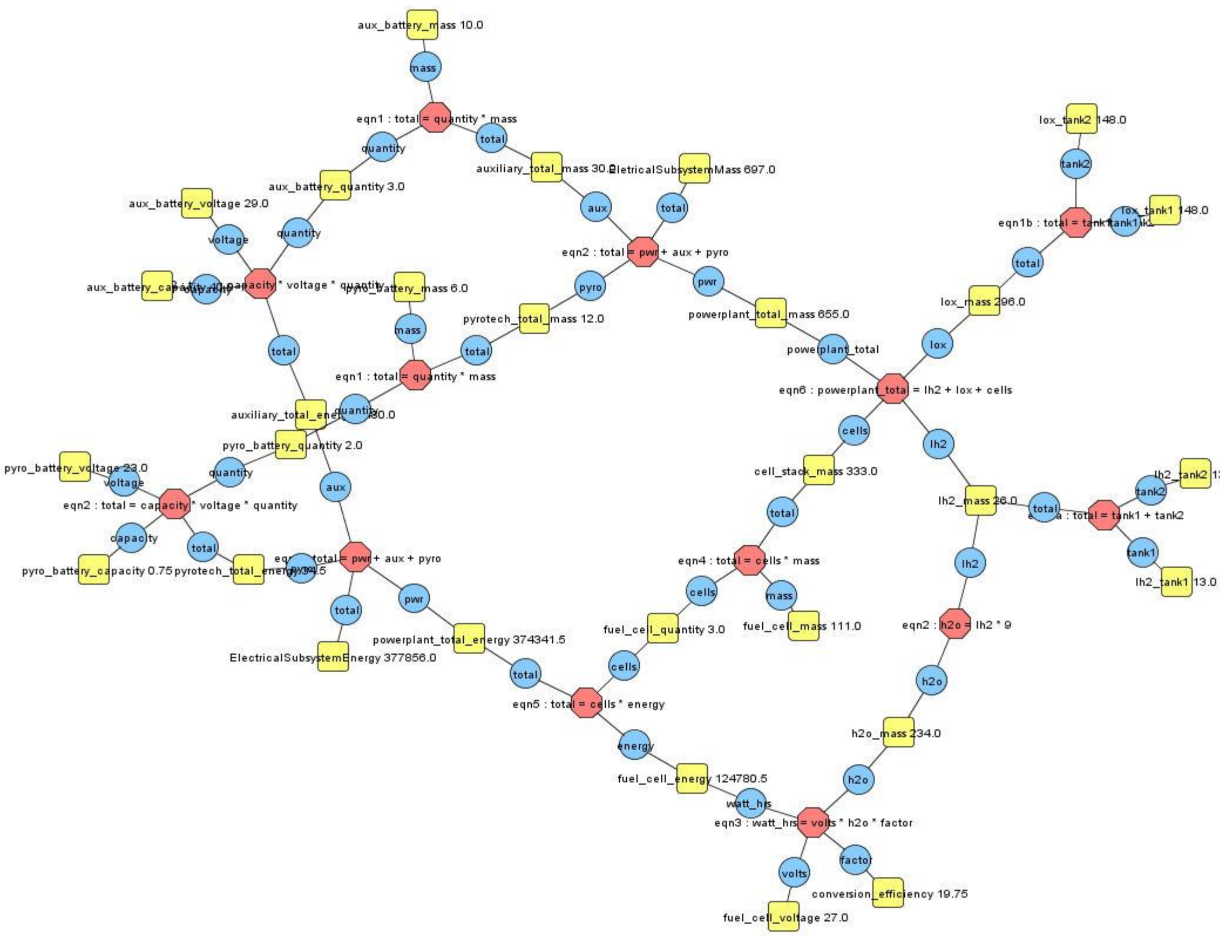

Figure 9 – Panorama organic visualization of the CSM electrical power subsystem.

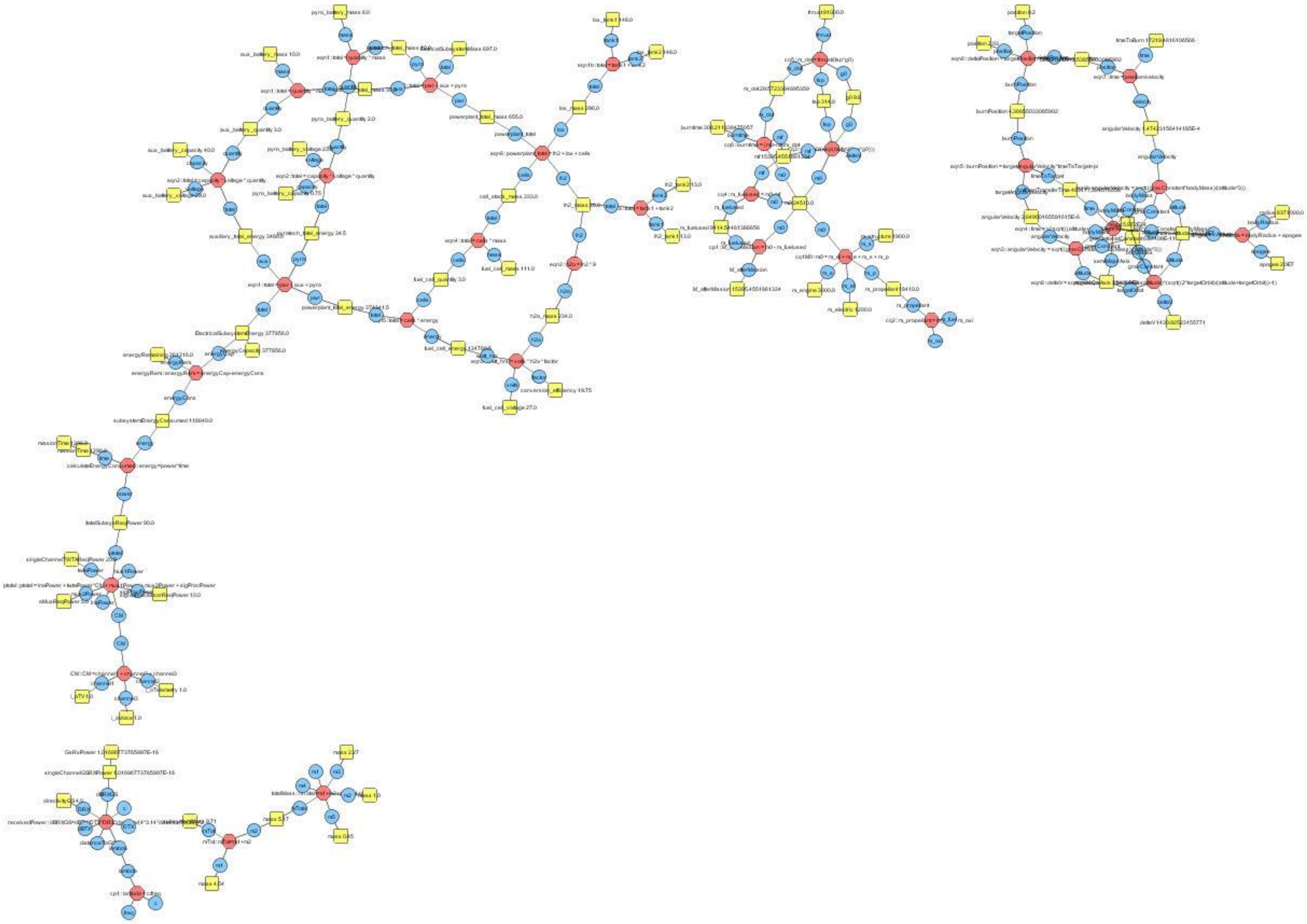

Figure 10 – Panorama organic visualization of the four command and service module subsystems integrated: radio communications, electrical power, orbital mechanics, and rocket propulsion.

III. References

[1] "Systems Data: Electrical Power Subsystem," *Apollo Operations Handbook, Block II Spacecraft*, Vol. 1, NASA Spacecraft Systems Operation Branch, SID 66-1508, 15 Oct 1969, section 2.6.

[2] "About the Apollo 11 Spacecraft- Apollo Fuel Cell Section," *National Air and Space Museum of the Smithsonian Institution* [webpage], [retrieved 15 Mar 2019], https://airandspace.si.edu/exhibitions/apollo-to-the-moon/online/apollo-11/about-the-spacecraft.cfm.

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[4] Munford, R.E, and Hendrix, B., "Apollo Experience Report - Command and Service Module Electrical Power Distribution Subsystem," NASA TN D-7609, Mar 1974.

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Section B: NASA FireSat II Research

I. FireSat II - Model Description & Details

FireSat II is the second iteration of a NASA proposed SmallSat for detecting and locating forest fires across the United States from low Earth orbit. Despite remaining a concept as of yet, there is an abundance of technical information publicly available on FireSat II from several preliminary mission reports. This has made FireSat II popular as a common reference for demonstrating various engineering methodologies for space systems, such as the books *Space Mission Engineering* and *Architecting Spacecraft with SysML*. The authors of the latter publication have even provided SysML files of FireSat II available online to be directly imported into MagicDraw. However, there are limitations with using this given model, due to its focus on behavioral elements with limited definitions of structure. Therefore, I set out to create my own parametric FireSat II model (inspired by the blocks provided in *Architecting Spacecraft*). The purpose of creating the model and an instance myself was to demonstrate the capabilities of the ParaMagic plugin for MagicDraw and the BuzzToys Panorama visualization tool. Due to project time constraints, only the communications and controls subsystems (and also part of the electrical subsystem) were created with a high level of fidelity. The remaining subsystems have given values for mass and power draw. Below are several diagrams depicting some of the components included in my final model.

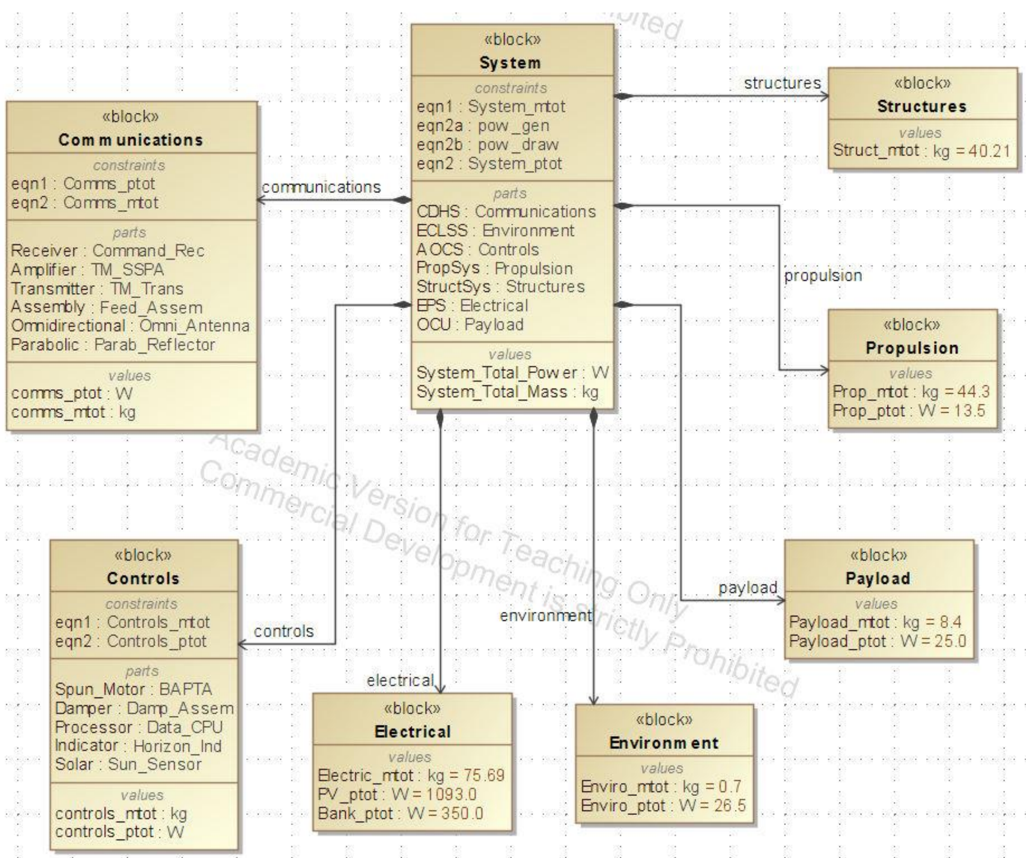

Figure 11 – Block definition diagram of FireSat II's interconnected subsystems.

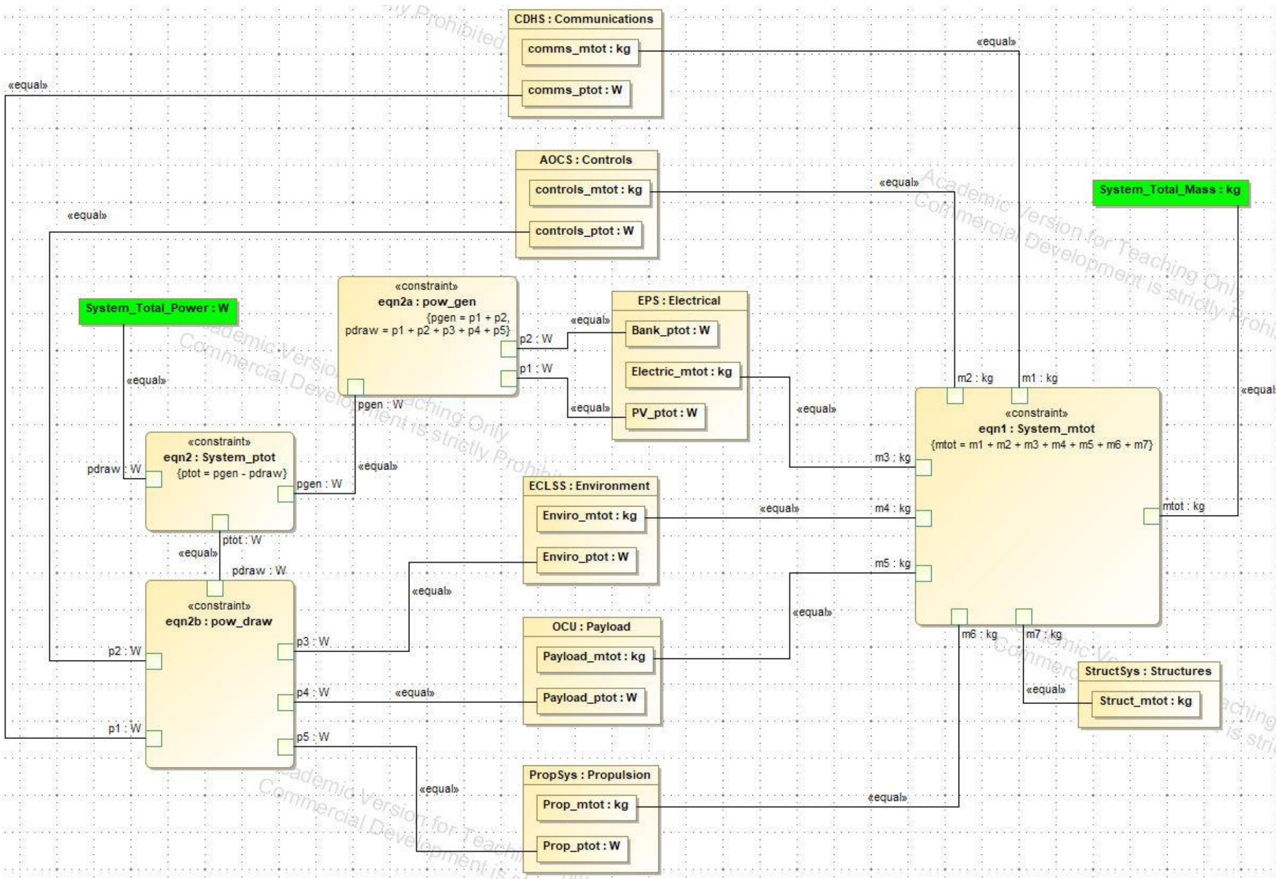

Figure 12 –The system's parametric diagram outputs values for total mass and power available.

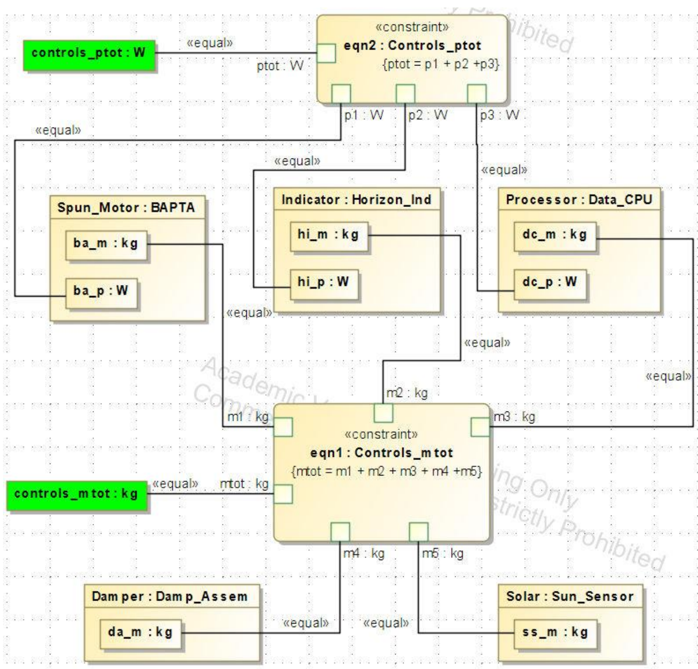

Figure 13 – SysML parametric diagram of the spacecraft's control system.

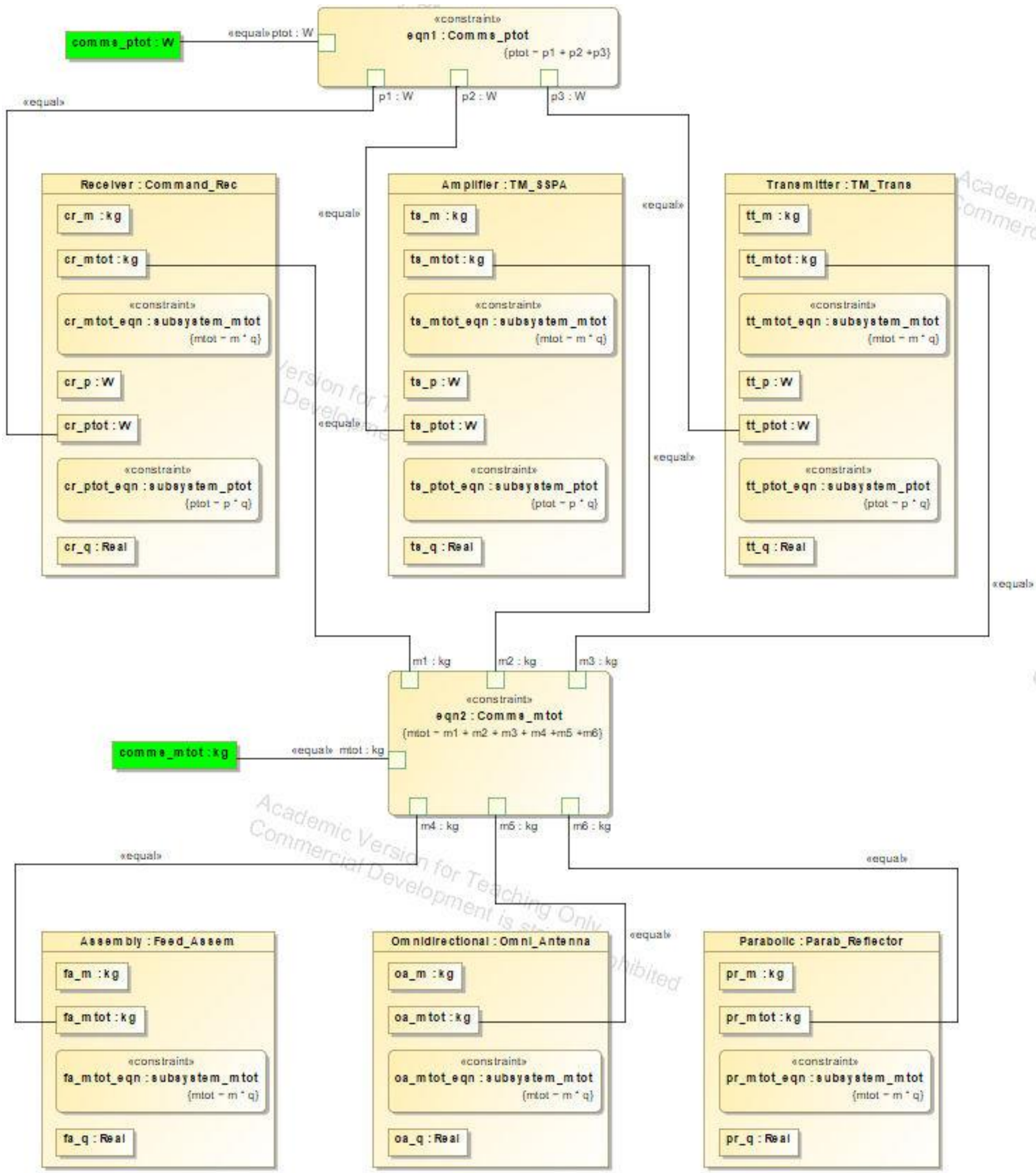

Figure 14 – The parametric diagram of the spacecraft's communications system is the most complex diagram created for the model. This complexity is largely due to the use of nested functions to account for varying multiplicities of components.

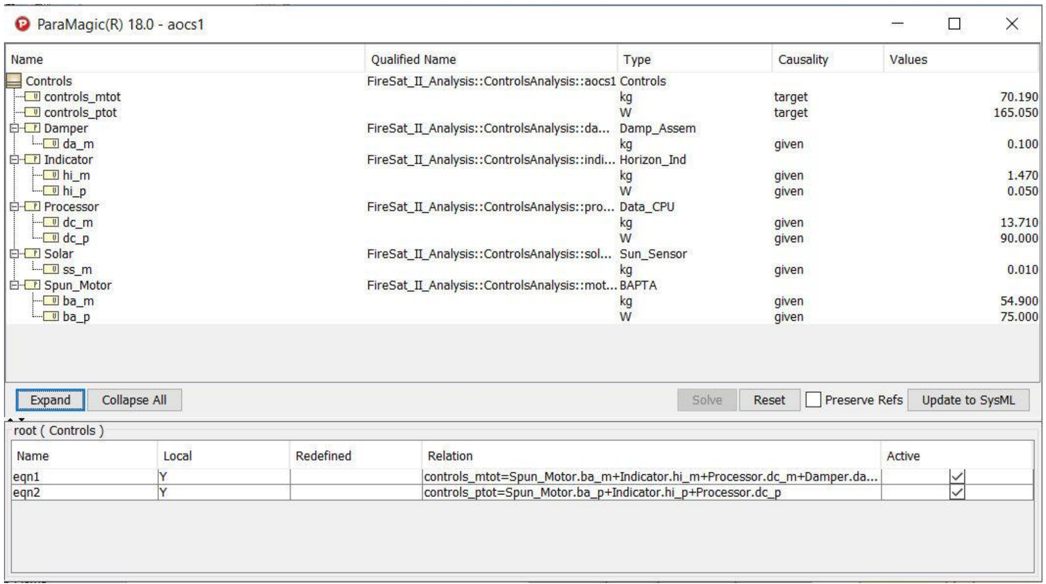

Figure 15 – ParaMagic calculating values for the controls subsystem instance called *aocs1*, using given values defined in the FireSat II mission proposal.

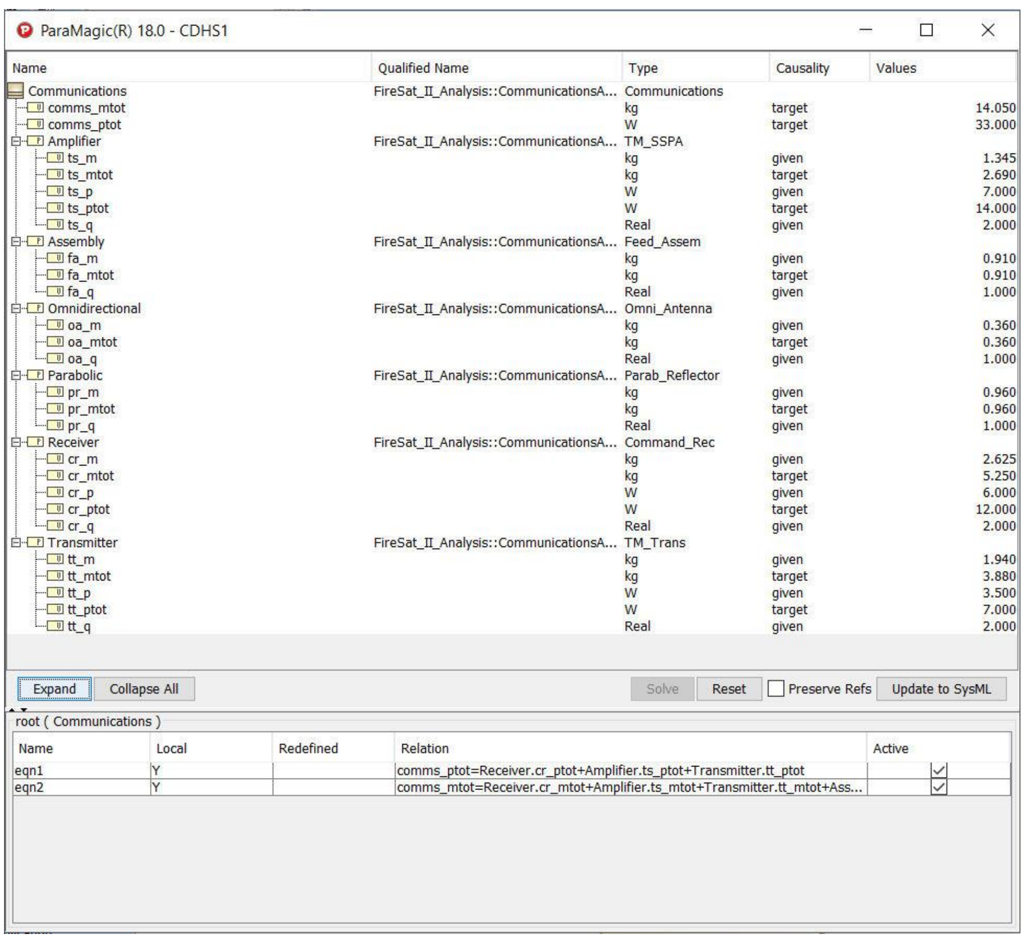

Figure 16 – ParaMagic calculating values for the communications instance *CDHS1*.

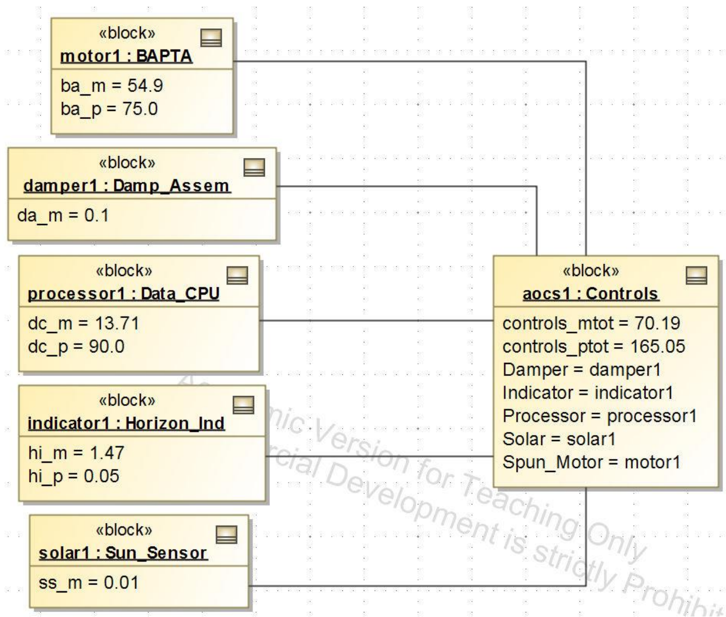

Figure 17 – Controls instance block definition diagram populated after solving with ParaMagic.

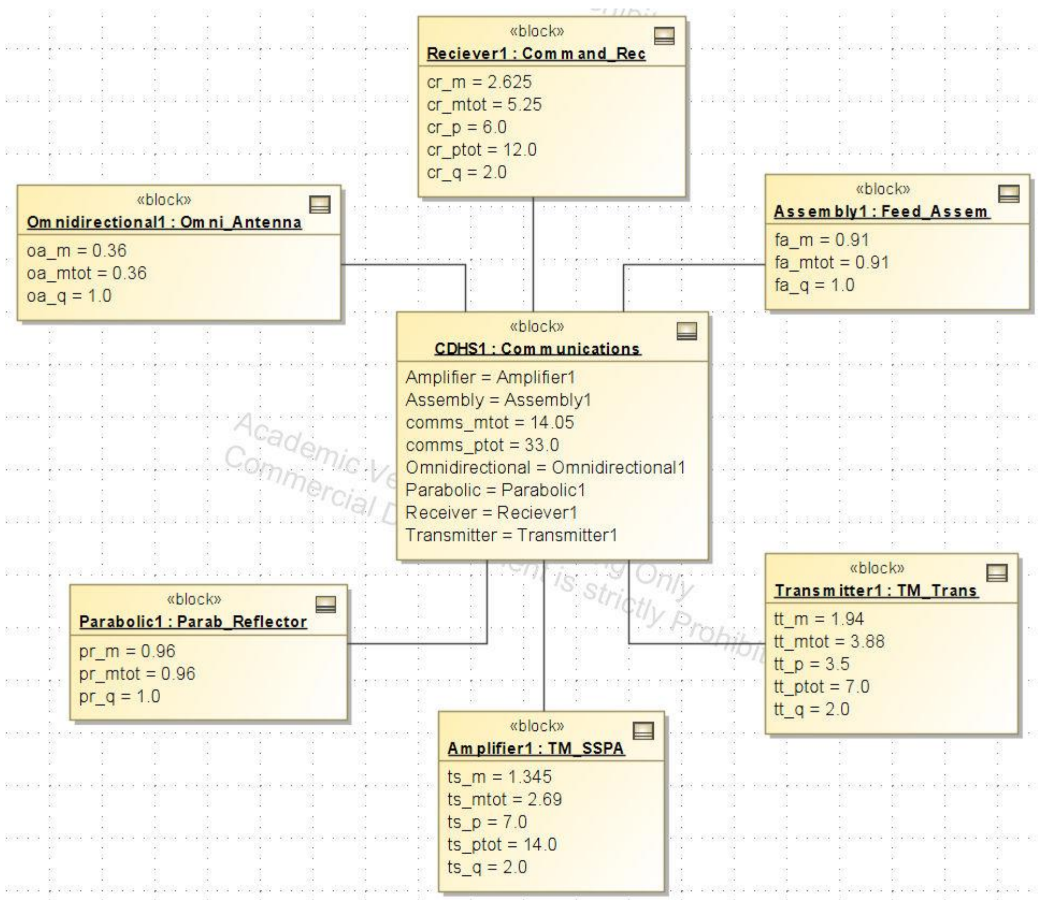

Figure 18 – Instance block definition diagram for communications subsystem.

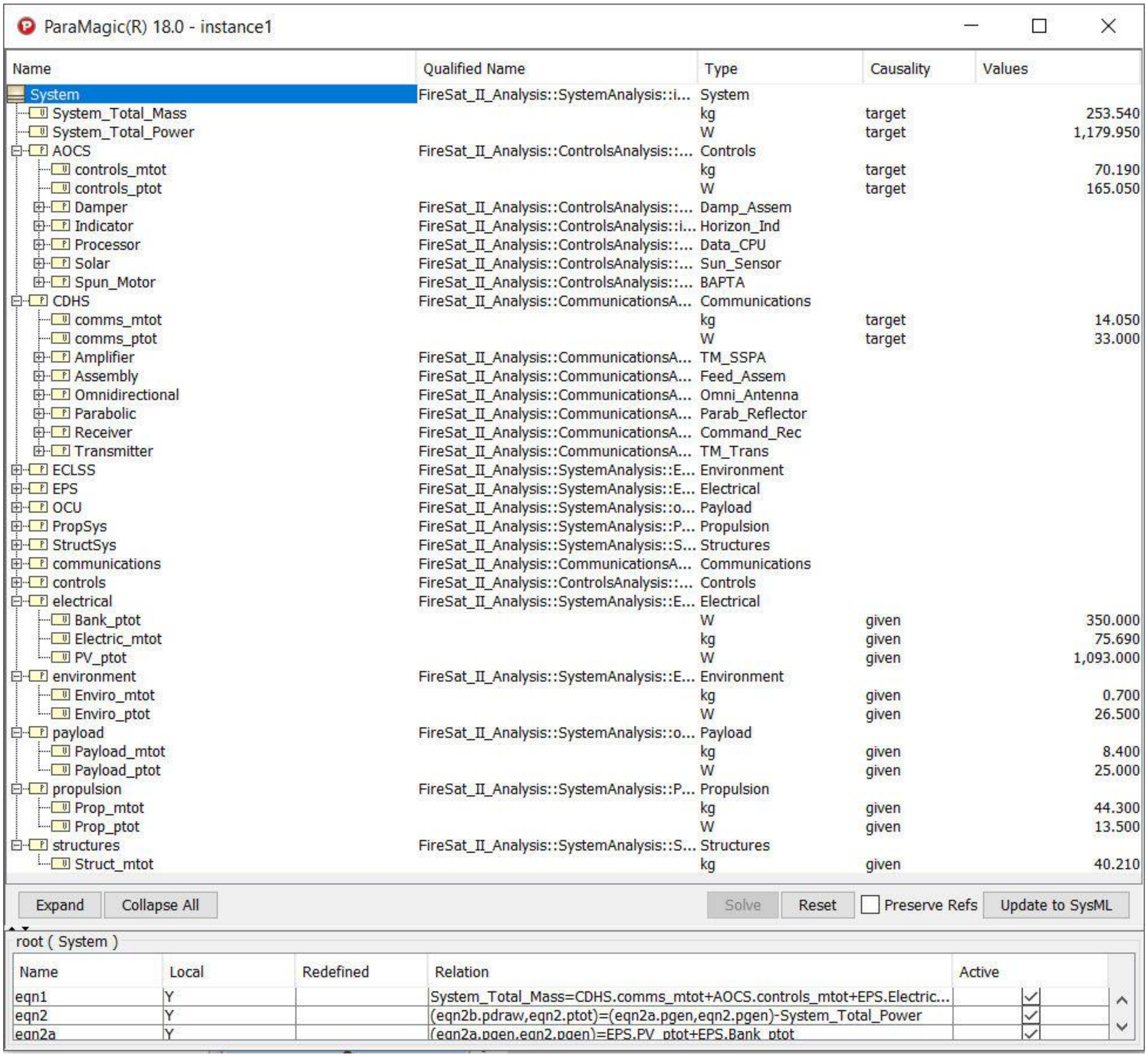

Figure 19 – ParaMagic calculating values for the completely integrated subsystems comprising the Fire Sat II spacecraft. Namely, this instance solves: the communications subsystem, the controls subsystem, the electrical subsystem, the environmental subsystem, the payload subsystem, the propulsion subsystem, and the structures subsystem.

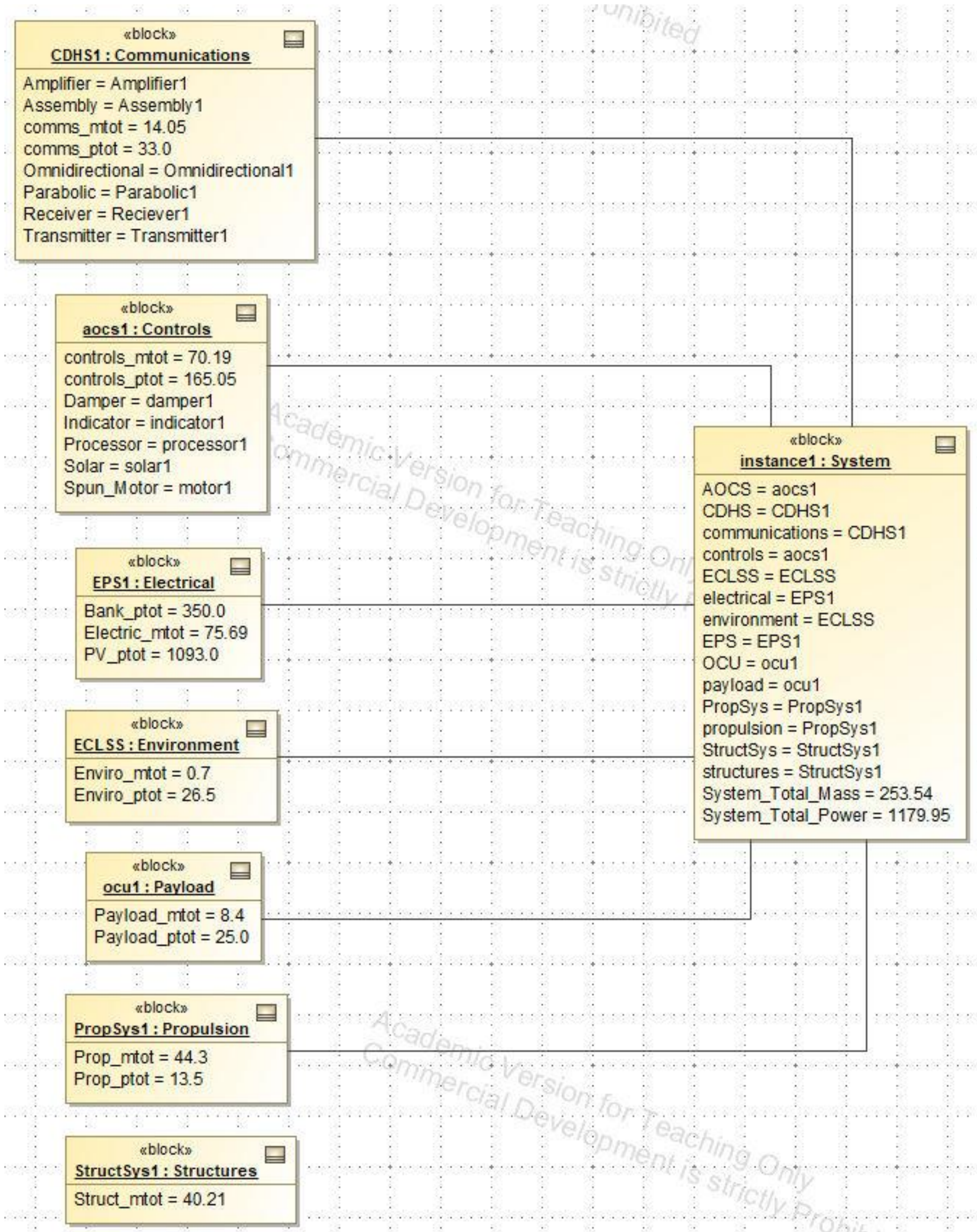

Figure 20 – Instance block definition for the entire FireSat II spacecraft system in *instance1*.

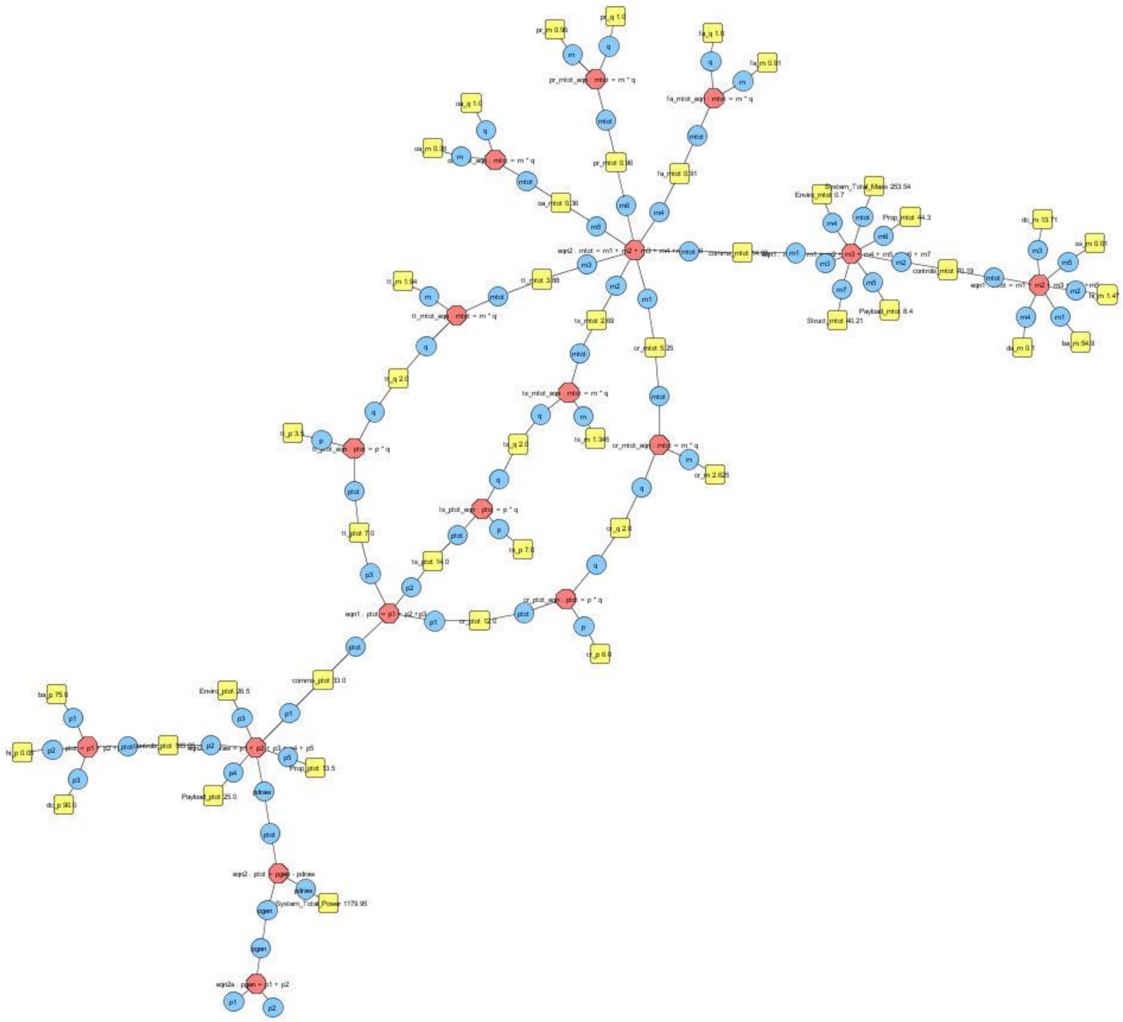

Figure 21 – Panorama DNA visualization of the interconnected FireSat II subsystems. Each subsystem contributes a power and mass value towards the total.

II. References

[1] Friedenthal, S., Oster, C., "SysML Models," [mdzip document], [retrieved 20 Apr 2019], http://sysml-models.com/spacecraft/models.html.

[2] "Space Mission Engineering: The New SMAD," Edited by Wertz, J.R., Everett, D.F., Puschell, J.J., 1st ed., Vol. 28, Microcosm Press, July 2011.

[3] Friedenthal, S., Oster, C., "Architecting Spacecraft with SysML," *Perform Design Analysis*, 1st ed., AIAA, Oct 2017, pp. 107-114.

[4] Vu, N., "The FireSat Project," *Systems Engineering Research Projects and Oral Presentations* [online], 32, 2010, pp. 1-31, http://digitalcommons.lmu.edu/se_etdrps/32.

[5] Delp, C., "INCOSE Space Systems Challenge Team and JPL MBSE," *Ground Vehicle Systems Engineering and Technology Symposium*, National Defense Industrial Association, Detroit, MI, 2012, pp. 1-42.